



Comparative Study of a New Sodium-Bentonite Clay for Use in the Pharmaceutical Industry

Madiar Beisebekov,^{1,2} Sana Kabdrakhmanova,^{1,*} Nurgamit Kantay,^{2,3,*} Aryp Kadiran,¹ Saule Nauryzova,¹ Esbol Shaimardan,² Kydyrmolla Akatan,^{3,*} Anastassiya Kukhareva,^{1,2} Aigul Baibotayeva,⁴ Zhansaya Lakhbayeva⁵ and Tulegen Seilkhanov⁶

Abstract

This study presents a comprehensive characterization of bentonite from the newly identified Orta Tentek deposit in southeastern Kazakhstan and evaluates the effect of hydro-activation with water on its physicochemical properties. The raw (Ot) and hydro-activated (Ot-H₂O) samples were analyzed using X-ray Fluorescence (XRF), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Brunauer–Emmett–Teller (BET) and Thermogravimetric Analysis (TGA)/Differential Thermal Analysis (DTA) techniques. XRF results revealed that Ot bentonite consists mainly of SiO₂ (66.2%), Al₂O₃ (18.1%), Fe₂O₃ (8.0%), and Na₂O (2.09%), with minor amounts of MgO, CaO, and TiO₂. The montmorillonite content reached 93%, and the methylene blue adsorption capacity was 93.2%. XRD confirmed that Ot bentonite corresponds to sodium montmorillonite, with an empirical formula of Na_{~0.2}Ca_{~0.1}Al_{~2}Si_{~4}O_{~10}(OH)_{~2}·nH₂O. Hydro-activation caused notable structural and textural modifications. The average particle size decreased by ~1.5-fold, while the BET surface area increased from 44.8 to 66.6 m² g⁻¹ and the average pore size from 3.2 to 4.2 nm. XRD revealed an increase in interlayer spacing and crystallite size. The methylene blue adsorption capacity also improved to 96%, reflecting enhanced sorption efficiency. The biological activity of Ot-H₂O aerobic bacteria increased by 2.4 times compared to Ot, while the biological activity of yeasts and molds increased by 1.8. These findings highlight the Ot bentonite as a promising natural resource. The improved d-spacing favors polymer intercalation in composites, the increased surface area enhances potential as a catalyst support, and the high sorption capacity demonstrates suitability for environmental remediation, drilling fluids, and pharmaceutical applications.

Keywords: Orta tentek deposit; Bentonite; Hydroactivation; Montmorillonite; Antibacterial; Structure; Sorption property; X-ray phase analysis.

Received: 29 October 2025; Revised: 02 December 2025; Accepted: 13 December 2025

Article type: Research article.

1. Introduction

Clay minerals are widely used in diverse industries such as agriculture, medicine, mechanical engineering, surface treatment, construction, and the petroleum sector.^[1] They are commonly classified into kaolinite, smectite, bentonite, montmorillonite, palygorskite, and sepiolite, based on their chemical composition, crystal structure, particle size and morphology, surface area, and other physicochemical properties. Distinct characteristics—including viscosity,^[1] mechanical strength,^[2] absorption and adsorption capacity,^[3] color-rendering ability,^[4] and resistance to abrasive wear^[5]

make clay minerals attractive for a wide range of applications. These include their use as binders, nano clays, and sealants in pharmaceuticals, construction, and chemical manufacturing.^[6]

Bentonites, a subgroup of natural clays, are extensively applied as catalysts in several chemical industries, including the production of gasoline and diesel fuels, as well as the processing of heavy crude oil.^[7] Montmorillonite, in particular, has been used as a photocatalyst to degrade toxic organic compounds in oil fields.^[8] It also serves as a binding agent in iron ore pelletizing^[9] and as a catalyst in biodiesel production, facilitating the esterification of free fatty acids (oleic, palmitic, and linoleic acids) with acetic acid and various alcohols such as propanol and butanol.^[10] Modified montmorillonite has been employed in the esterification of maleic acid with ethanol,^[11] as well as in the transesterification of *Jatropha curcas* and soybean oils using different alcohols.

In environmental applications, activated palygorskite combined with montmorillonite has been utilized for the

¹Satbayev University, Almaty, 050013, Kazakhstan

²Scientific Center of Composite Materials, Almaty, 050000, Kazakhstan

³S. Amanzholov East Kazakhstan University, Oskemen, 070000, Kazakhstan

⁴Al-Farabi Kazakh National university, Almaty, 050040, Kazakhstan

recovery of heavy metals such as Pb^{2+} , Cu^{2+} , and Hg^{2+} ^[12] Modified montmorillonite has also proven effective in removing metals including Cu^{2+} , Co^{2+} , and Pb^{2+} from aqueous solutions.^[13] Moreover, montmorillonite has been successfully applied to eliminate a variety of pollutants, including chlorothalonil pesticides, ciprofloxacin, arsenic from alkaline water and aromatic hydrocarbons such as m-xylene and toluene.^[14]

Recent studies have focused on developing composite systems with enhanced performance using bentonite. Examples include composites with styrene and acrylic acid, cryogels based on polyvinyl alcohol (PVA) and gelatin for the adsorption of Cu^{2+} , Ni^{2+} , Fe^{2+} , Cd^{2+} , and Pb^{2+} ions,^[15] and monocation-exchanged bentonites integrated with flocculants for the removal of dyes from wastewater.^[16]

Kazakhstan is rich in high-quality clay mineral resources, offering a cost-effective source of raw materials for various industries. One notable example is Tagan bentonite, located in the Tarbagatai area of East Kazakhstan, near Zhanazhol village.^[17] Tagan bentonite is distinguished by its purity (low content of harmful heavy metals), high porosity, mechanical strength, and adsorption capacity. Known commercially as the “Tagan sorbent,” this clay has been developed into powder, biologically active supplements, and gels enriched with silver and potassium ions. Its ion-exchange capabilities enable the removal of toxic heavy metals such as Pb, Cd, U, and radionuclides, while simultaneously releasing essential elements, thereby aiding detoxification processes in the liver and lungs.^[18] Its unique smectite structure also underpins its antibacterial activity, making it suitable for medical applications.

Tagan bentonite has demonstrated efficiency in wastewater treatment for the removal of Mn^{2+} , Co^{2+} , and Ni^{2+} ions.^[19] Additionally, Kalzhat clay modified with silver and copper nanoparticles exhibited strong antibacterial activity against Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli*, with inhibition zones ranging from 8.5 to 25 mm.^[20,21] These findings highlight the potential of functionalized clays as antibacterial agents for medical and agricultural applications.

Other studies have examined bentonites from the Kalzhat (Almaty region) and Orta Tentek (Zhetysu region) deposits, focusing on the effects of acid modification with 5–10% HCl.^[21] Acid treatment led to the leaching of Ca, K, Mg, Ba, Zn, Al, and Mo ions, while slightly increasing Fe and some other elements. This process substantially reduced the content of alkaline and alkaline-earth metals, decreasing the negative

zeta potential and thereby altering surface charge and colloidal stability.

Overall, the literature demonstrates that the composition and properties of natural clays vary considerably depending on their origin and processing method. Functionalization with nanoparticles (*e.g.*, Ag, Cu) has been shown to enhance their mechanical, antibacterial and other properties.^[22]

In studies,^[23,24] the physicochemical and textural properties of bentonite were investigated by activating it with low-concentration aqueous electrolyte solutions of sodium, potassium, and calcium. As a result, a decrease in the electrostatic attraction between negatively charged particles was established. Moreover, the concentration of monovalent and divalent cations increased. This, in turn, improved the sorption properties of the bentonite. In study,^[25] it was found that during water activation, the crystal lattice of bentonite undergoes hydration, its dispersity and colloidal properties increase, and its sorption and ion-exchange characteristics are improved. This enables its safe application in the food industry and pharmaceuticals.

Despite the abundance of bentonite deposits in Kazakhstan, the Orta Tentek clay—located on the right bank of the Orta Tentek River in the Alaöl District of the Zhetysu region (80°59'46"E, 45°48'09"N)—remains largely unexplored. To date, there has been limited research on its elemental composition, phase structure, morphology, textural parameters, adsorption–desorption behavior, and thermal stability.

According to geological exploration data, the total reserves are estimated at approximately 58 million tons. Moreover, since it is located close to settlements, excavation and transportation do not present any difficulties. This may have a positive effect on the low cost of the obtained material.

In this regard, the aim of this work was to study the elemental composition, structural-phase state, morphology, textural parameters, and thermal stability of the Ot bentonite found at the above-mentioned coordinates, as well as to compare the effect of water activation on its physicochemical characteristics and to determine the possibility of pharmaceutical use through comparative studies of microbiological activity.

2. Materials and methods

2.1 Materials

The research material was bentonite collected from the Orta Tentek deposit, situated on the right bank of the Orta Tentek River in the Alakol District of the Zhetysu region, Republic of Kazakhstan (Fig. 1). The raw sample was designated as Ot, whereas the hydro-activated sample, obtained by treatment with deionized water, was labeled as Ot-H₂O. Deionized water served as the sole medium for the modification procedure.

The Kalzhat deposit is located in the Uyghur district of Almaty Region, near the village of Kalzhat (43°30'32" N, 80°40'22" E). Geographically, the area belongs to the northwestern periphery of the Dzungarian Gate, a major wind

⁵Abai Kazakh National Pedagogical University, Almaty, 050010, Kazakhstan

⁶The laboratory of engineering profile of NMR spectroscopy, Sh.Ualikhanov Kokshetau University, Kokshetau, 020000, Kazakhstan

*Email: skabdrakhmanova@gmail.com (S. Kabdrakhmanova), nurgan85@mail.ru (N. Kantay), ahnur.hj@mail.ru (K. Akatan)

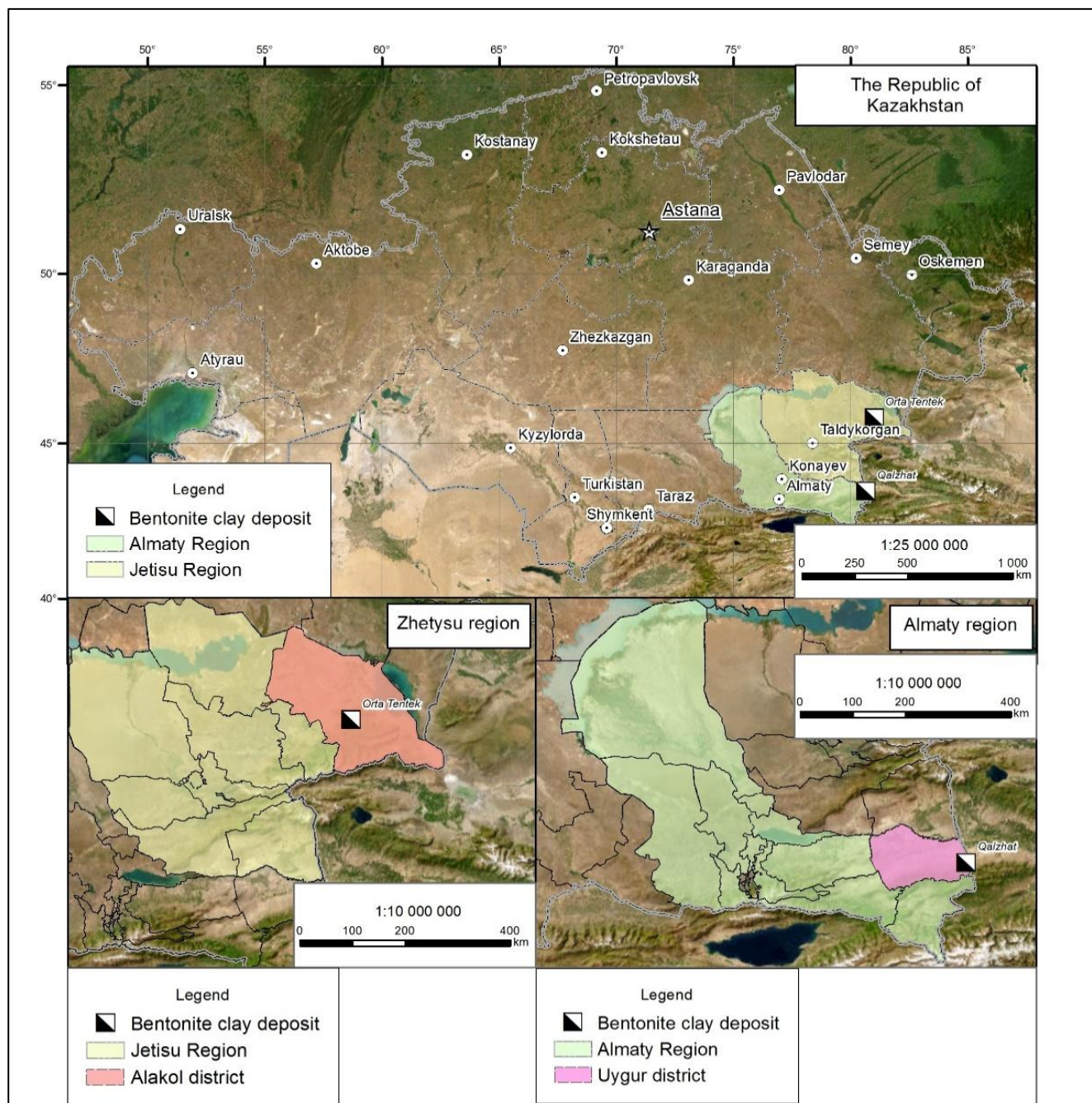


Fig. 1: Geographic location map of the Ot bentonite.

corridor between the Dzungarian Alatau and the Barlyk Range. The climate is classified as cold semi-arid (BSk according to Köppen), characterized by low precipitation and strong persistent winds. Landscapes are represented by piedmont plains and gently undulating hills with sparse ephemeral vegetation. Geologically, the deposit is associated with the southern margin of the Balkhash–Ili fold belt. The section is mainly composed of Neogene–Quaternary lacustrine–alluvial and proluvial sediments of the piedmont apron, with interbeds and lenses of clay. Mineralogical investigations (XRD, XRF, SEM-EDS) indicate the presence of mixed-layer clays of the kaolinite–illite type with glauconite, muscovite, and quartz admixtures, dominated by SiO_2 (≈ 44 – 62 wt.%) and Al_2O_3 (≈ 9 – 21 wt.%). In several horizons, smectitic phases have been

identified, which impart bentonitic properties. The genesis of the deposit is related to the diagenetic transformation of lacustrine–alluvial sediments with local smectitization of volcanogenic–clastic materials. Although the bentonite quality of Kalzhat clays is confirmed in laboratory tests, no official quantitative reserve estimates have been published to date, and reliable resource evaluation will require additional geological exploration.^[26]

The Orta Tentek deposit is situated in the Zhetysu Region, within the basin of the Tentek River (Orta Tentek – “Middle Tentek”), on the northeastern slopes of the Dzungarian Alatau, in the Alakol depression ($45^\circ 48' \text{ N}$, $80^\circ 59' \text{ E}$; 822 m a.s.l.). The locality is associated with the river valley and its exit from the mountain gorge near the village of Bibikan. The climate is

Table 1: Comparative characteristics of the Kalzhat and Orta Tentek clay deposits.

Parameter	Kalzhat	Orta Tentek
Location	Uyghur District, Almaty Region; ~43°30'N, 80°40'E	Zhetysu Region, Alakol depression; ~45°48'N, 80°59'E
Geomorphology	Piedmont plain, gently undulating hills, sparse ephemeral streams	Piedmont plain with narrow gorges, river terraces along Tentek valley
Climate	Cold semi-arid (BSk), low precipitation, strong winds (Dzungarian Gate)	Sharply continental, 150–260 mm/yr in lowlands, up to 550 mm in mountains
Geological setting	Southern margin of the Balkhash–Ili fold belt; Neogene–Quaternary lacustrine–alluvial and proluvial deposits	Kolpakov intermontane depression; Miocene lacustrine clays with sand/gravel, overlain by Pleistocene–Holocene alluvium
Mineralogy	Mixed-layer kaolinite–illite clays, with glauconite, muscovite, quartz; SiO ₂ 44–62%, Al ₂ O ₃ 9–21%	Dominated by SiO ₂ and Al ₂ O ₃ ; smectitic (montmorillonitic) phases identified in several samples
Genesis	Diagenetic transformation of lacustrine–alluvial deposits with partial smectitization of volcanogenic detritus	Smectitization of volcanogenic ash under lacustrine conditions; redeposition in alluvial terraces
Economic significance	Clays tested for bentonitic properties and modification potential; no reserve estimates published	Smectite-rich clays promising for adsorption/modification technologies; no reserve estimates published

sharply continental: annual precipitation does not exceed 150–260 mm in the lowlands and reaches 350–550 mm in the mountains. The landscape includes piedmont plains, narrow gorges, and fluvial terraces, composed of Pleistocene–Holocene alluvial deposits. In the subsurface, colorful Miocene lacustrine clays with interlayers of sand and gravel are widespread, reflecting the history of a large paleolake in the Alakol depression. Bentonitization of certain horizons is associated with smectitization of volcanogenic ash material under lacustrine sedimentation conditions, followed by redeposition in the alluvial system of the Tentek River. Mineralogical analyses confirm high contents of SiO₂ and Al₂O₃ and the presence of smectitic (montmorillonitic) phases in several samples, making the raw material promising for adsorptive and modification technologies.^[27] However, as in the case of Kalzhat, there are currently no publicly available reserve estimates for Orta Tentek. Table 1 shows comparative characteristics of both deposits.

Overall, the Kalzhat and Orta Tentek deposits represent important occurrences of bentonitic clays in southeastern Kazakhstan. Their study is of academic interest for reconstructing sedimentary and volcanogenic processes in the Dzungarian and Alakol geostructural zones, and of practical significance for the potential development of Kazakhstan's bentonite resource base. At present, the lack of officially reported reserves highlights the need for detailed geological exploration and resource evaluation

2.2 Methods

2.2.1 Activation of Ot bentonite with water

Hydro-activation of Orta Tentek (Ot) bentonite was performed following the method described by Salo *et al.*^[28] For this purpose, 50 g of bentonite was dispersed in 1 L of deionized

water and continuously stirred with a magnetic stirrer at 1000 rpm for 8 h. The resulting suspension was then heated to 90 ± 2 °C and stirred for an additional 2 h. The material was subsequently filtered under vacuum, dried at 100 ± 2 °C for 6 h to constant weight, and stored in a desiccator to prevent adsorption of moisture and CO₂ from air. The water-modified bentonite was designated as Ot-H₂O.

2.2.2 Qualitative characteristics

The qualitative characteristics of bentonites were determined according to GOST 28177-89 standards.

The moisture content. The method is based on determining the loss of mass after drying a sample of clay at a temperature of 105–110 °C. The mass fraction of moisture (X) in percent is calculated using the Eq. (1):

$$X = (m - m_1) / m_1 \cdot 100 \quad (1)$$

where m - is the mass of the clay sample before drying, g; m₁ - is the mass of the clay sample after drying, g.

The montmorillonite fraction. The determination of montmorillonite content by adsorption luminescence analysis is based on the cation-exchange adsorption of organic luminophore dyes by clay, resulting in the formation of an organoclay complex coagulate.

Methylene blue adsorption capacity. Not less than 150 mg of methylene blue per 1 g of substance, calculated on a dry basis. This determination is carried out by spectrophotometry (Pharmacopoeia of the Republic of Kazakhstan "Spectrophotometry in the Ultraviolet and Visible Regions").

2.2.3 X-ray fluorescence spectroscopy (XRF)

The oxide composition of the samples was determined using an advanced EDXRF Rigaku NEX CG II spectrometer

(Japan). This instrument employs polarized X-ray beams for high-sensitivity elemental analysis in the Na–U range. The X-ray tube was operated at 50 kV/50 W or 65 kV/100 W, and detection was performed using a large-area silicon drift detector (SDD).

2.2.4 X-ray diffraction analysis (XRD)

Phase composition was analyzed using an X'pert PRO diffractometer (PANalytical, Netherlands) with CuK α radiation ($\lambda = 1.54056 \text{ \AA}$, $U = 40 \text{ kV}$, $I = 30 \text{ mA}$) in point mode. Scans were collected over $10\text{--}70^\circ 2\theta$ with a step size of 0.02° in Bragg–Brentano geometry. Data were processed using *HighScore Plus* software.

CSL was determined via the Scherrer Eq. (2):

$$\text{CSL} = k\lambda/\beta\cos\theta \quad (2)$$

where k is a shape factor that is often 0.9; λ is the wavelength of the diffractometer (0.1542 nm); β is the FWHM (maximum half of the full width) of the diffraction peak in radians; and, θ is the diffraction angle.

2.2.5 Scanning electron microscopy (SEM)

Morphology was examined by SEM using an Auriga Crossbeam 540 (Carl Zeiss, Oberkochen, Germany). Imaging was performed at 5 kV accelerating voltage, scanning speed of 2, and magnification suitable for $1\text{--}100 \text{ }\mu\text{m}$ resolution. Samples were coated with a thin Au film to improve structural contrast.

2.2.6 Fourier-transform infrared spectroscopy (FTIR)

FTIR spectra were recorded on an FT-801 spectrometer (Simex, Russia) in the $450\text{--}4700 \text{ cm}^{-1}$ range with 1 cm^{-1} resolution. Measurements were carried out at 25°C using both attenuated total reflection (ATR) and specular-diffuse reflection (SDR) modes.

2.2.7 Brunauer–Emmett–Teller (BET) surface area

The specific surface area and porosity parameters were determined using a BSD-660 analyzer (China), which measures surface areas $\geq 0.0005 \text{ m}^2 \text{ g}^{-1}$, pore diameters between $0.35\text{--}500 \text{ nm}$, and pore volumes $\geq 0.0001 \text{ cm}^3 \text{ g}^{-1}$.

2.2.8 Thermogravimetric and differential thermal analysis (TGA/DTA)

Thermal stability was investigated by simultaneous thermogravimetric (TGA) and differential scanning calorimetry (DSC) using an SKZ1060A analyzer (China). Experiments were conducted under nitrogen flow in the $30\text{--}800^\circ\text{C}$ range, at a heating rate of $10^\circ\text{C}/\text{min}$.

2.2.9 Microbiological analysis

The analysis of the total microbiological purity of bentonite clay was carried out in accordance with the State Pharmacopoeia of the Republic of Kazakhstan (pp. 176–180, section 2.6.12) using the deep inoculation method. Sample

preparation was performed in accordance with the subsection “Water-insoluble medicinal products not containing fats.” The samples were taken randomly, one gram of the test sample was carefully suspended in 9 mL (a 1:10 dilution, or 10^{-1}) of sterile 0.9% sodium chloride solution containing peptone with a pH of 7. Serial tenfold dilutions were then prepared up to 10^{-6} using the same diluent.

Into 90 mm Petri dishes, 1 mL of the prepared sample (as described above) and 15–20 mL of molten nutrient medium, cooled to no more than 45°C , were poured. For bacterial cultivation, Meat-Peptide Agar was used; for fungal cultivation, Sabouraud medium was used. Incubation was carried out at $30\text{--}35^\circ\text{C}$ for 48 hours for bacteria and at $20\text{--}25^\circ\text{C}$ for 5 days for fungi.

Colony counting was performed on plates containing 30–300 colonies ($10\text{--}100$ for fungi), and the number of viable microorganisms (CFU/mL) was calculated taking into account the dilution factor and inoculated volume. For each dilution, two Petri dishes with the corresponding nutrient medium were used.

To calculate the number of viable microorganisms (CFU/mL), the following Eq. (3) was used:

$$N = \frac{C}{V} \times \frac{1}{d} \quad (3)$$

where: N – concentration of microorganisms in the original sample (CFU/mL), C – number of colonies on the plate (CFU), V – inoculated volume (mL), d – dilution factor.

3. Results and discussion

3.1 XRF analysis of Ot bentonite

The comparative XRF analysis results of the initial Ot and water-activated Ot-H $_2$ O bentonites are presented in Table 2. According to the obtained results, the chemical composition of the bentonite consists of complex oxide mineral mixtures. The elemental composition of the initial Ot bentonite was found to predominantly consist of SiO $_2$ (66.2%), Al $_2$ O $_3$ (18.1%), Fe $_2$ O $_3$ (8.00%), Na $_2$ O (2.09%), and approximately 1% MgO, CaO, and TiO $_2$. Trace amounts of heavy metals (0.0033–0.0536%) were also detected, the content of which does not exceed the maximum allowable concentration according to the Pharmacopoeia article.^[3] Additionally, the presence of elements such as Mg, Fe, Ca, Na, and K, which are capable of cation exchange, contributes to the characteristic elemental composition of montmorillonite,^[9,21] as identified in studies. This, in turn, positively influences the cation exchange capacity and sorption properties of the Ot bentonite.^[29]

After activation with water, it was found that the amounts of some oxides in the Ot bentonite decreased slightly. Specifically, the levels of SiO $_2$ (0.3%), Al $_2$ O $_3$ (0.7%), Fe $_2$ O $_3$ (1.62%), Na $_2$ O (0.33%), and CaO (0.23%) decreased. This is due to being closely related to the hydrolysis of weakly bound ions during water activation.^[28] Furthermore, the Si/Al ratio in the initial Ot composition was 3.6, while after water

Table 2: Chemical composition of initial Ot and water-modified Ot-H₂O bentonites based on XRF analysis.

Component	Initial Ot (mass %)	Ot-H ₂ O (mass %)
SiO ₂	66.2 ± 0.0555	65.9 ± 0.049
Al ₂ O ₃	18.1 ± 0.0762	17.4 ± 0.0671
Fe ₂ O ₃	8.00 ± 0.0061	6.38 ± 0.0048
Na ₂ O	2.09 ± 0.0059	1.76 ± 0.0021
CaO	1.03 ± 0.0032	0.80 ± 0.0048
MgO	1.53 ± 0.215	2.03 ± 0.182
TiO ₂	0.952 ± 0.0028	0.759 ± 0.002
K ₂ O	0.555 ± 0.0043	0.524 ± 0.0037
P ₂ O ₅	0.156 ± 0.0023	0.132 ± 0.0019
SrO	0.0662 ± 0.0001	0.0027
MnO	0.0536 ± 0.0006	0.0460 ± 0.0005
BaO	0.0369 ± 0.0007	0.0132 ± 0.0004
V ₂ O ₅	0.0346 ± 0.0009	0.0279 ± 0.0007
Co ₂ O ₃	0.0235 ± 0.0010	0.0213 ± 0.0008
NiO	0.0120 ± 0.0002	0.0101 ± 0.0001
CuO	0.0084 ± 0.0001	0.0068 ± 0.0001
ZnO	0.0064 ± 0.0001	0.0056 ± 0.0001
Rb ₂ O	0.0050 ± 0.0001	0.0039 ± 0.0001
Ga ₂ O ₃	0.0047 ± 0.0001	0.0035 ± 0.0001
Y ₂ O ₃	0.0042 ± 0.0001	0.0031 ± 0.0001
Nb ₂ O ₅	0.0027 ± 0.0002	0.0017 ± 0.0001
Ag ₂ O	0.0009 ± 0.0001	0.0005 ± 0.0001
Remaining components	1.2	1.0

Table 3: Quality indicators of initial Ot and Ot-H₂O bentonites.

Sample	H ₂ O (moist) percentage, %	Montmorillonite percentage in bentonite, %	Methylene blue adsorption properties, %
Ot	13.8 ± 1	93 ± 3	93.2 ± 3
Ot-H ₂ O	8.4 ± 0.5	93 ± 3	96 ± 3

activation, the Si/Al ratio became 3.7. Studies^[30] have shown that the Si/Al ratio in bentonite typically ranges between 3 and 5, which is characteristic of montmorillonite bentonites. The Si/Al ratio of the Ot bentonite identified in this study corresponds to that of montmorillonite bentonites.

3.2 Quality indicators of Ot bentonites

Table 3 summarizes the values of moisture content, montmorillonite fraction, and methylene blue adsorption capacity for both raw Ot and hydro-activated Ot-H₂O bentonites. The initial Ot bentonite exhibited a moisture content of 13.8%, a montmorillonite content of 93%, and a methylene blue adsorption capacity of 93.2%. In the Ot-H₂O sample, the moisture content decreased to 8.4%, which can be attributed to the reduced physical adsorption of inherent moisture following hydro-activation. The montmorillonite content remained nearly unchanged compared to the raw sample. In contrast, the methylene blue adsorption capacity increased to 96%, reflecting the effect of hydro-activation. This improvement is associated with the removal of residual impurities and water-soluble minerals, as well as the expansion of interlayer spaces within the silicate structure.^[31]

3.3 FTIR analysis

Fig. 2 presents the FTIR spectra of raw Ot and hydro-activated Ot-H₂O bentonites, while Table 4 summarizes the corresponding absorption bands. The structural interpretation was made by comparison with earlier studies.^[31] Overall, the spectra are typical of aluminosilicate minerals. Consistent with the XRF data (Table 1), Ot bentonite consists predominantly of SiO₂ (66.2%) and Al₂O₃ (18.1%).

In the spectrum of raw Ot (Fig. 2a), the band at 528.7 cm⁻¹ corresponds to Si–O and Si–O–Al stretching vibrations, while the band at 697.9 cm⁻¹ is assigned to Si–OH and Al–OH twisting and Al–O stretching vibrations. The band at 777.7 cm⁻¹ is characteristic of Si–O–Al bonds in bentonite, whereas the bands at 796.0 and 915.7 cm⁻¹ correspond to Al–Mg–OH and Al–Al–OH groups, respectively. The strong absorption at 1031.5 cm⁻¹ represents in-plane Si–O stretching of layered silicates. The band at 1640.2 cm⁻¹ is attributed to H–O–H bending vibrations of adsorbed water, while the broad absorptions at 3442.2 and 3628.9 cm⁻¹ correspond to O–H stretching in Al–OH/Si–OH groups and interlayer water molecules.

The spectrum of hydro-activated Ot-H₂O (Fig. 2b) shows

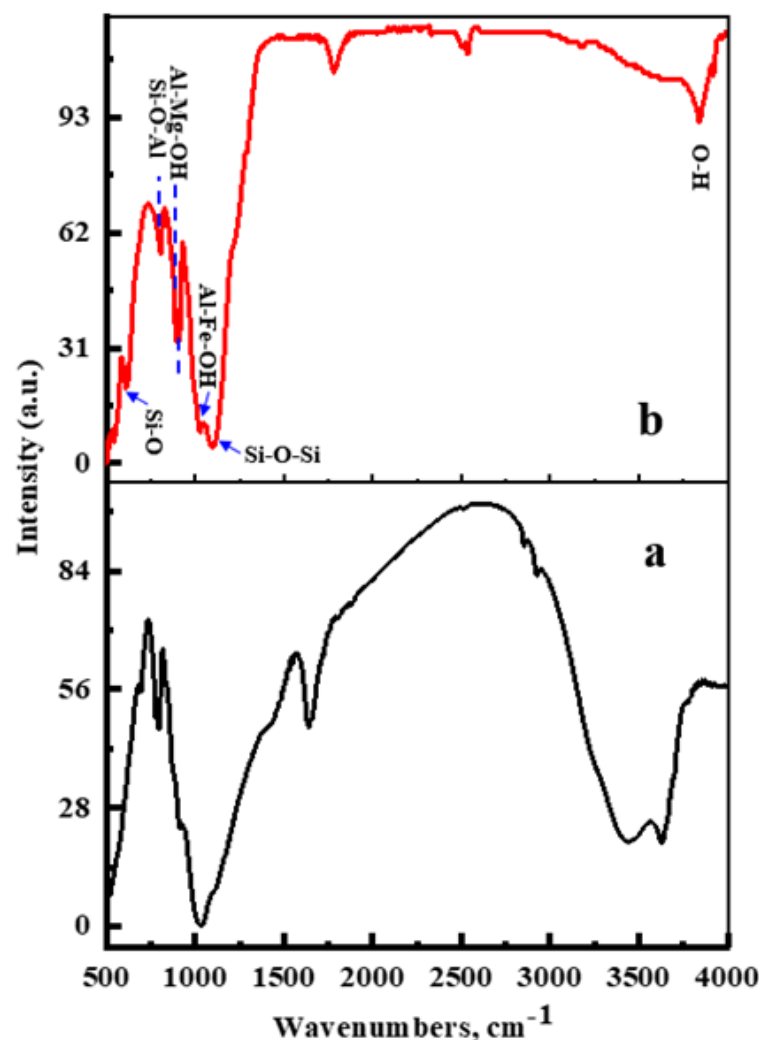


Fig. 2: The comparative FTIR spectra of the initial Ot (a) and water-activated Ot-H₂O (b).

no major structural changes compared with raw Ot. However, the intensities of characteristic bands are enhanced, indicating improved signal resolution. Table 3 provides the numerical values of these bands. The increased band intensities may be related to the partial removal of weakly bound SiO₂ and Al₂O₃ during water activation.^[32] This observation is consistent with the reduction in oxide concentrations detected by XRF (Table 1). Furthermore, the band at 3842.6 cm⁻¹, associated with O–H groups of water molecules coordinated to interlayer cations (Na⁺, Ca²⁺, K⁺, Mg²⁺), decreased in intensity, reflecting dehydration of crystallization water bound to exchangeable ions. According to previous studies,^[1,32] such structural modifications during hydrothermal treatment arise from partial dissolution of silica and alumina and the loss of interlayer water associated with exchangeable cations.

3.4 XRD analysis

The crystal structure of initial Ot and hydro-activated Ot-H₂O bentonites was examined by X-ray diffraction (XRD) (Fig. 3). Phase identification was carried out using the ICDD Powder Diffraction File database (PDF# 01-089-6535) in accordance with earlier studies.^[33] The diffractograms of Ot and Ot-H₂O

were largely similar, indicating that hydro-activation does not alter the overall crystal structure or phase composition of the bentonite. However, a decrease in diffraction peak intensities was observed in Ot-H₂O, which can be attributed to partial hydrolysis and leaching of interlayer Ca²⁺ and Mg²⁺ cations, consistent with the XRF and FTIR findings (Tables 2 and 4).^[34]

The results confirm that montmorillonite is the principal component of Ot bentonite, with a monoclinic lattice belonging to the C2/m space group. This is consistent with the result indicating that the montmorillonite content in the Ot bentonite, as determined in Table 2, is 93%. The Si/Al ratio obtained from XRF is typical of montmorillonite and supports this interpretation. Representative basal reflections for the raw Ot sample were identified as d001 = 14.35 Å (2θ = 6.3°), d002 = 4.47 Å (2θ = 19.8°), and d003 = 3.03 Å (2θ = 29.4°) (Table 4). The basal peak at 2θ = 6.3° (d001 = 14.35 Å) confirms the predominance of Na⁺ in the interlayer positions.^[35] In addition, the peak at 2θ = 26.7° (d = 3.34 Å) corresponds to crystalline quartz (SiO₂, trigonal, space group P3₁21/P3₂21).^[35] The overall structural framework of Ot bentonite consists of 2:1 layered silicates, with two tetrahedral Si–O sheets sandwiching an octahedral Al/Mg–O sheet.^[34]

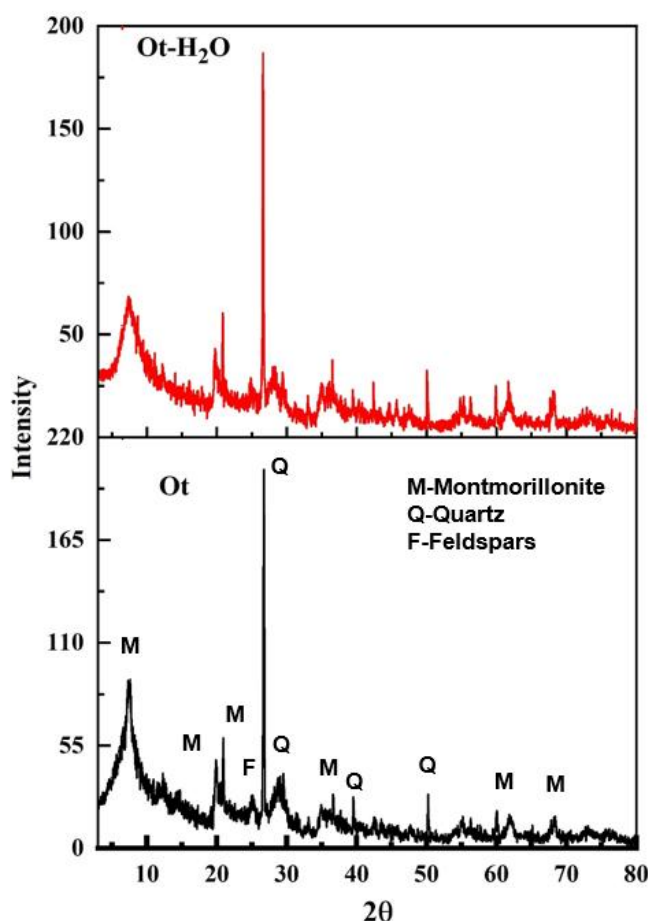


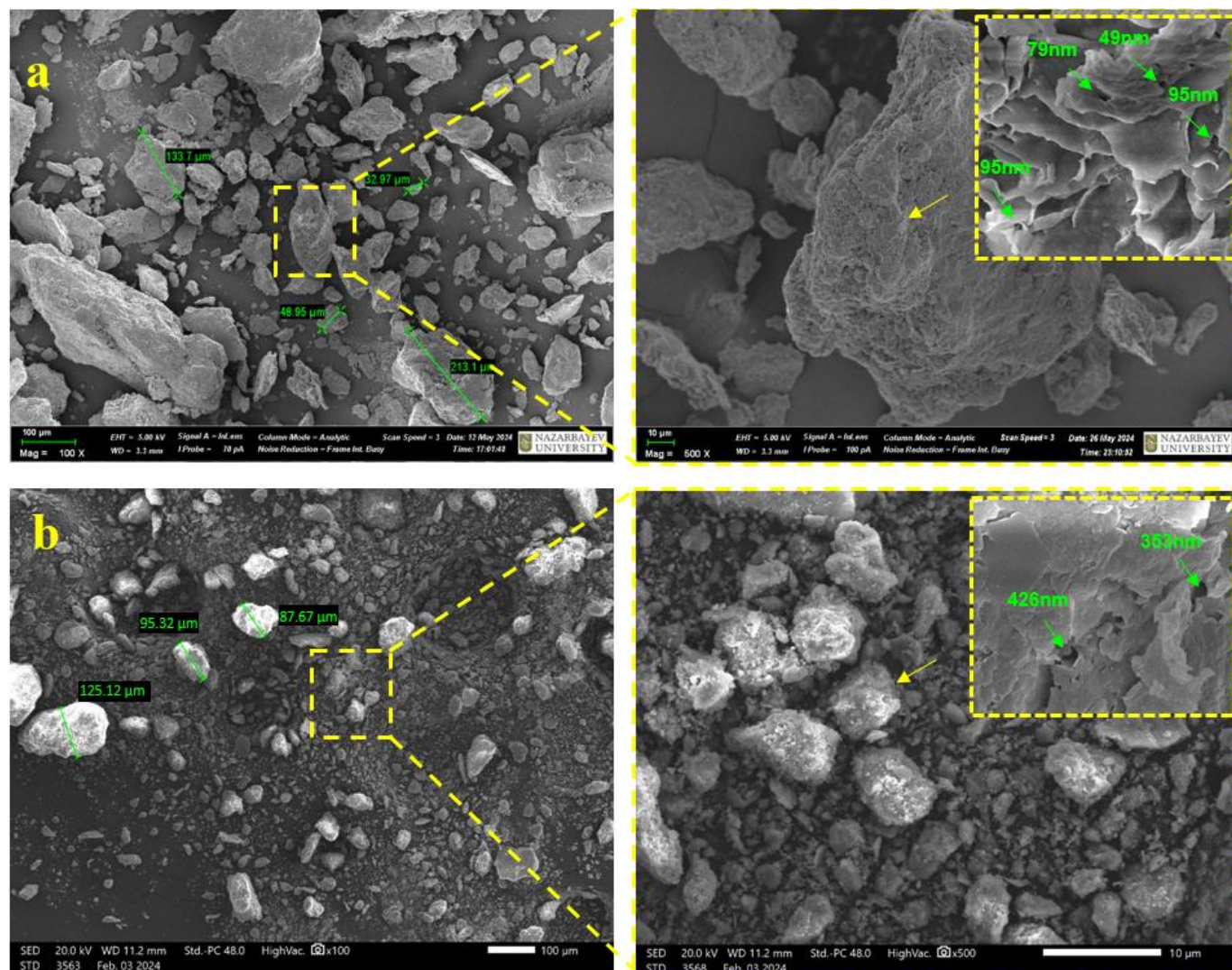
Fig. 3: X-ray diffractograms of the initial Ot and water-activated Ot-H₂O.

Table 4: FT-IR band positions of the initial Ot and Ot-H₂O.

Initial Ot				Ot-H ₂ O			
Absorption (cm ⁻¹)	Appearance	Group	Compound class	Absorption (cm ⁻¹)	Appearance	Group	Compound class
528.72	Medium	Si-O, Si-O-Al	Silicon monoxide, Alkyl halides	550.8	Medium	Si-O, Si-O-Al	Silicon monoxide, Alkyl halides
697.9	Medium	Si-O, Si-O-Al	Alkynes, Benzene derivatives	613.2	Medium	Si-O, Si-O-Al	Alkynes, Benzene derivatives
777.7	Medium	Si-O-Al	bentonite clay	804.8	Medium	Si-O-Al	Quartz
796.0	Medium	Al-Mg-OH	1,2,3-trisubstituted	892.0	Medium	Al-Mg-OH	1,2,3-trisubstituted
915.7	Weak broad	Al-Fe-OH	Aromatics, Octahedral	914.28	Weak broad	Al-Fe-OH	Aromatics, Octahedral
1031.5	Strong	Si-O-Si	Tetrahedral	1028.19	Strong	Si-O	Tetrahedral
1094.22	Strong	Si-O-Si	Tetrahedral	1640.2	Strong	H-O-H	Physisorbed
1226.9	Weak broad	Si-O	Out of plane Si-O stretching for montmorillonite	1782.75	Medium	H-O-H	Physisorbed
2520.32	Medium	O=C=O	Absorbed CO ₂	3442.2	Strong	H-O-H	Absorbed H ₂ O
3540.45	Medium	O-H	Absorbed H ₂ O	3628.9	Strong	O-H	OH band stretch for Al-OH, Si-OH and Fe ³⁺ -Fe ²⁺ -OH
3842.56	Strong	O-H	OH band stretch for Al-OH, Si-OH and Fe ³⁺ -Fe ²⁺ -OH				

Table 5: The typical peak parameters in the XRD diffractograms of Ot and Ot-H₂O.

Ot				Ot-H ₂ O			
2θ	hkl	d, Å	Crystal size, nm	2θ	hkl	d, Å	Crystal size, nm
6.3	001	14.35	11.72	6.3	001	14.49	17,59
19.8	002	4.47	22.75	19.7	002	4.51	26,74
29.4	003	3.03	33.4	29.4	003	3.04	36,32

**Fig. 4:** SEM microphotograph of the Orta Tentek bentonite: a) Ot; b) Ot-H₂O.

Based on the PDF# 01-089-6535 data, the empirical formula of Ot bentonite was determined as $\text{Na}_{\sim 0.2}\text{Ca}_{\sim 0.1}\text{Al}_{\sim 2}\text{Si}_{\sim 4}\text{O}_{\sim 10}(\text{OH})_{\sim 2}\cdot\text{N}_2\text{H}_2\text{O}$, confirming its classification as sodium bentonite. The absence of significant mixed phases contributes positively to its swelling, sorption, and plasticity properties, enhancing its potential applications in drilling fluids, adsorbents, construction materials, medicine, and agriculture.

The Ot-H₂O sample exhibited the same characteristic peaks as raw Ot (Table 5), but with slightly increased interlayer spacing (d) and crystallite size. These changes are associated with hydration of exchangeable interlayer cations by water molecules during activation.^[34] Previous studies have similarly reported that hydration, intercalation with organic

molecules, and thermal treatment can induce reorganization of silicate layers in montmorillonite-based clays.^[34]

3.5 SEM analysis

The surface morphology of initial Ot and hydro-activated Ot-H₂O bentonites was examined by SEM (Fig. 4). As shown in Fig. 4a, the raw Ot bentonite is composed of irregularly shaped granules formed by the agglomeration of plate-like particles. The surface of these granules appears rough and porous, with pore diameters ranging from 49 to 95 nm. The particle size distribution is heterogeneous, with an average particle size of approximately 165 μm. These observations are consistent with previous reports indicating that montmorillonite-group bentonites are composed of plate-like granules that aggregate

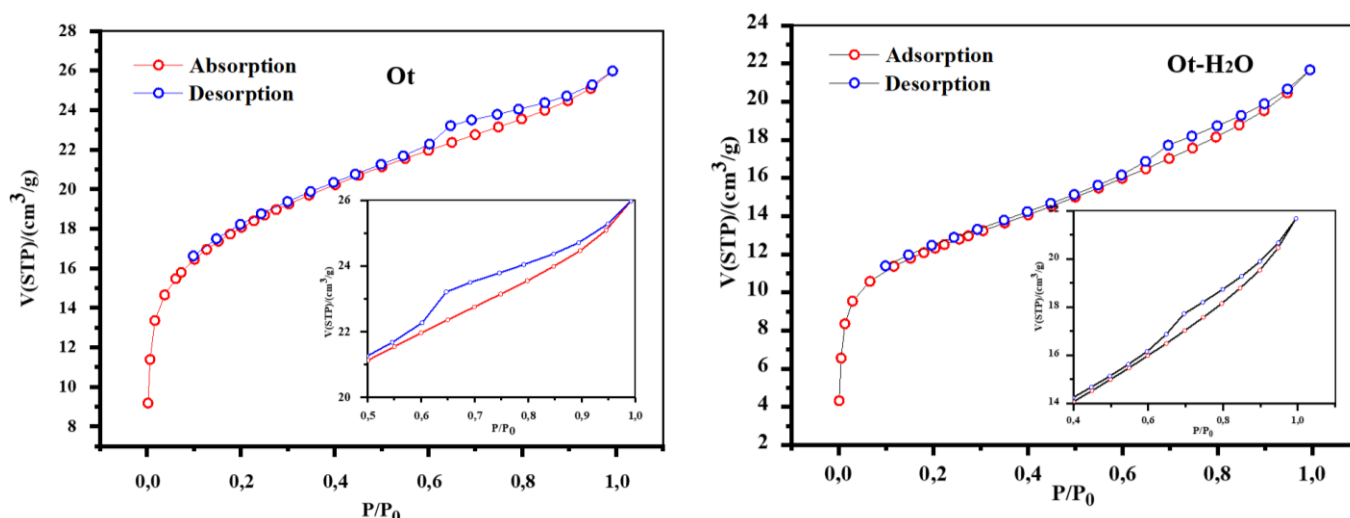


Fig. 5: N₂ adsorption/desorption isotherms of the initial Ot and water-activated Ot-H₂O bentonite.

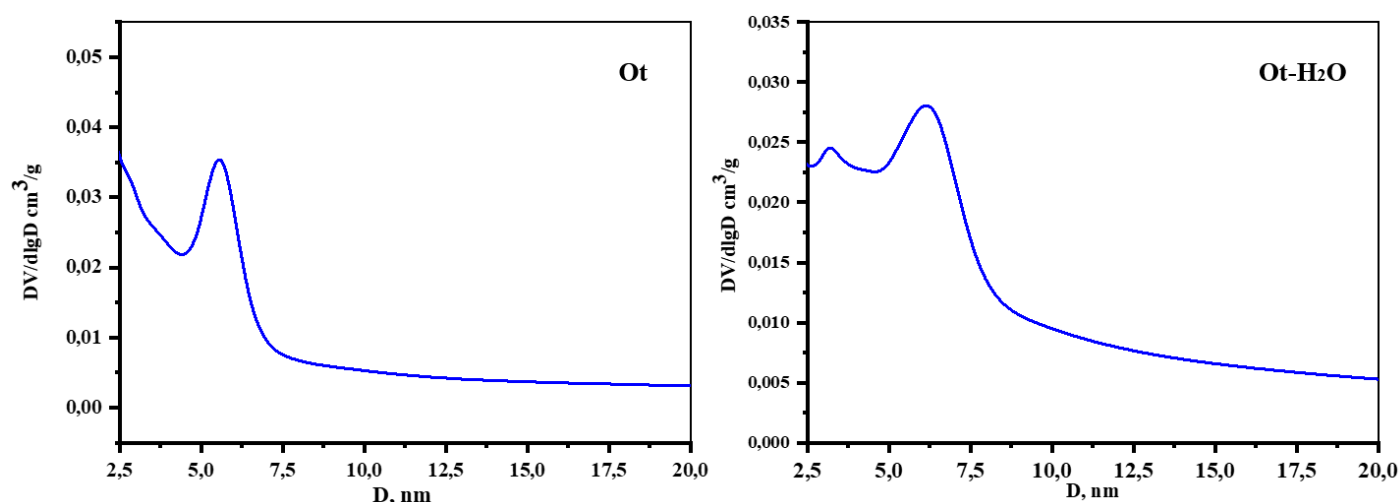


Fig. 6: Average pore sizes of the initial Ot and water-activated Ot-H₂O bentonite.

into porous structures,^[36] further confirming the montmorillonite nature of Ot bentonite.

In contrast, the Ot-H₂O sample (Fig. 4b) displayed smaller average particle sizes (~100 μm), about 1.5 times smaller than the raw sample, along with a significant increase in pore size values, ranging from 353 to 426 nm (approximately 4.8-fold larger). In addition, the surfaces of the agglomerated granules appeared smoother and more uniform after hydro-activation. These changes may be attributed to enhanced Van der Waals interactions following water treatment, which promote the compaction and reorganization of plate-like particles.^[37]

3.6 BET analysis

The N₂ adsorption–desorption isotherms and average pore size distributions of Ot and Ot-H₂O bentonites are shown in Figs. 5 and 6. Both samples exhibit type IV isotherms with H4-type hysteresis loops according to the IUPAC classification.^[38] Such hysteresis is characteristic of microporous–mesoporous adsorbents with slit-shaped or bottle-neck pores. These results indicate that Ot bentonite contains both micropores and mesopores, with mesopores dominating the pore structure.

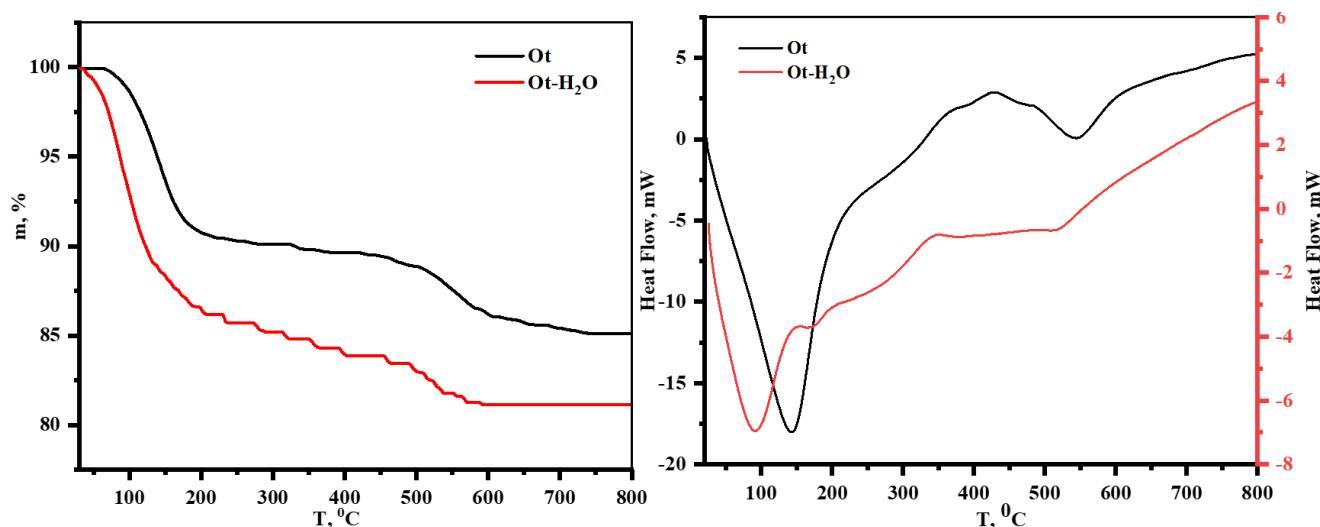
Capillary condensation during adsorption occurs via cylindrical menisci, whereas capillary evaporation during desorption proceeds through hemispherical menisci, giving rise to the hysteresis loop and confirming the mesoporous nature of the material.^[39] The pronounced nitrogen uptake at low relative pressures reflects micropore filling, while the continuous adsorption at higher pressures indicates the presence of mesopores or larger external surface areas. The rounded “knee” of the isotherm at low pressures also suggests the presence of wider micropores, implying a broad pore size distribution and variable pore geometries.

Water activation enhanced the adsorption capacity of Ot bentonite (Table 6). This improvement is likely due to the removal of weakly bound mineral impurities and partial reorganization of the interlayer structure.^[40] The increase in interlayer spacing observed by XRD (Fig. 3) supports this interpretation, as hydration of exchangeable cations promotes expansion of the silicate layers.

Textural parameters (Table 6) further confirm these trends. The initial Ot sample exhibited a BET surface area of 44.79 m² g⁻¹, with 45.73% micropores, 54.27% mesopores, an

Table 6: Textural parameters values for initial Ot and Ot-H₂O.

		Ot	Ot-H ₂ O
Surface area, m ² /g		44.79	66.62
Pores volume	m ³ /g	0.0204 (micro)	0.0107 (micro)
		0.0200 (meso)	0.0169 (meso)
	%	45.73 (micro)	31.88 (micro)
		54.27 (meso)	68.13 (meso)
External specific surface area, m ² /g		18.95	19.4
Average pore size, nm		3.21	4.03

**Fig. 7:** Comparative thermograms of the initial Ot and water-activated Ot-H₂O bentonite samples.

average pore diameter of 3.21 nm, and an external surface area of 18.95 m² g⁻¹. After hydro-activation, Ot-H₂O showed a BET surface area of 66.62 m² g⁻¹—approximately 1.5 times higher than initial Ot. The mesopore fraction increased by 1.3-fold, and the external surface area slightly increased to 19.4 m² g⁻¹. These enhancements in surface area and mesoporosity may be attributed to nanoscale crystal reorganization and the exchange of larger interlayer cations with smaller hydrated cations.^[41,42]

3.7 TGA analysis

Fig. 7 presents the comparative thermogravimetric (TGA) curves of initial Ot and hydro-activated Ot-H₂O bentonites. The thermal changes can be divided into three main stages:

Stage 1 (30–180 °C):

The initial Ot sample exhibited a mass loss of ~9.8%, whereas the Ot-H₂O sample showed a higher mass loss of ~16%. This reduction is attributed to the evaporation of physically adsorbed water from the bentonite surface. The endothermic peak observed in the DTA curve at 100–200 °C corresponds to this dehydration process.^[43]

Stage 2 (190–600 °C):

In this region, mass losses of ~14% (Ot) and ~19% (Ot-H₂O) were recorded. These changes are associated with the dehydroxylation of structural –OH groups tightly bound within the montmorillonite layers.^[44] A minor exothermic effect at ~500 °C in the DTA curve supports this interpretation.

Stage 3 (600–800 °C):

Beyond 600 °C, no significant weight loss was observed, indicating that the remaining ~83% of the material consists of thermally stable aluminosilicate frameworks and metal oxides.^[45] This stability is consistent with the XRF results (Table 1), which revealed a composition rich in oxides. Similar thermal behavior has been reported for bentonites with high montmorillonite content.^[46]

3.8 Comparative analysis

Table 7 summarizes the key results obtained for initial Ot and hydro-activated Ot-H₂O bentonites in comparison with data from other studies. The moisture contents of Ot and Ot-H₂O did not differ significantly. However, the montmorillonite content of both Ot samples was approximately two times higher than that of Oued Zemmour bentonite,^[47] and comparable to Cuban bentonite.^[48] Since a higher montmorillonite fraction generally enhances sorption properties, this indicates the favorable adsorption potential of Ot bentonites.

In terms of textural parameters, the specific surface area values of Cuban bentonite^[48] and Pogodayevo modified bentonites^[49] were about 1.5 times greater than those of Ot, Ot-H₂O, and Oued Zemmour bentonites.^[49] By contrast, the average pore sizes of all samples were relatively similar. These results suggest that despite lower surface area compared to certain bentonites, the Ot bentonite from the Orta Tentek

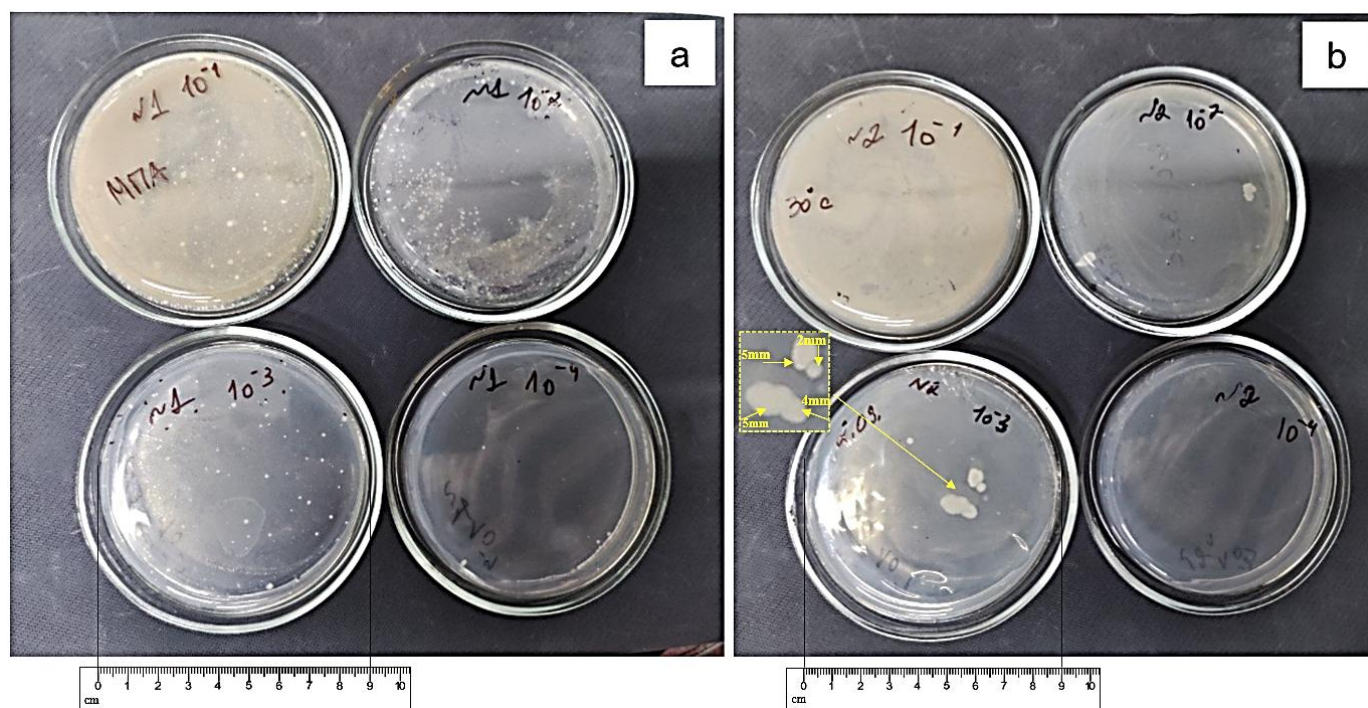


Fig. 8: Total Plate Count of bacteria expressed as colony-forming units (CFU): a – Ot; b – Ot-H₂O.

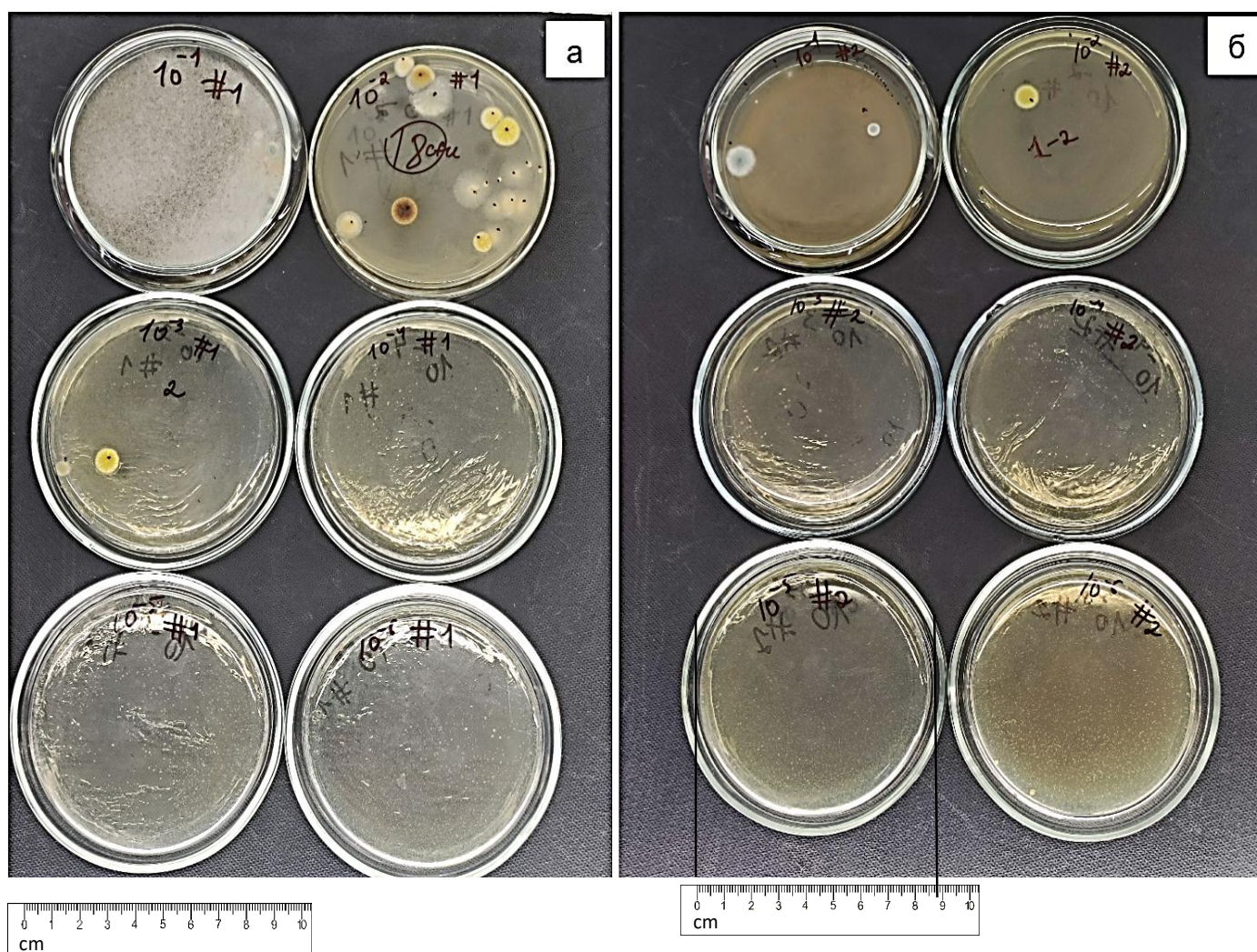


Fig. 9: Total Plate Count of yeasts and molds expressed as colony-forming units (CFU): a-Ot; b-Ot-H₂O.

Table 7: Comparative values of key quantitative indicators of Ot and Ot-H₂O with other studies.

Samples	H ₂ O (moist) percentage, %	Montmorillonite percentage in bentonite, %	Average pore size, nm	Specific surface area, m ² /g
Ot	13.8	93	3.21	45.79
Ot-H ₂ O	8.4	93	4.03	66.62
Oued Zemmour Bentonite ^[42]	10.69	44	3.5	58.20
Cuban bentonite ^[48]	undefined	~90	5.2	80.10
Pogodayevo Modified bentonites ^[49]	undefined	undefined	8.3	86.03

Table 8: Determination of the total number of viable aerobic bacteria (CFU/mL). TNTC – Too Numerous To Count, TFTC – Too Few To Count.

Dilution factor	Trial 1	Trial 2	Average number of colony-forming units (CFU)	Acceptability	CFU/mL
Ot					
10 ⁻¹	>250	>250	>250	TNTC	—
10 ⁻²	250	240	245	Countable	2,45 × 10 ⁴
10 ⁻³	27	25	26	TFTC	—
10 ⁻⁴	2	3	2,5	TFTC	—
10 ⁻⁵	0	0	0	TFTC	—
10 ⁻⁶	0	0	0	TFTC	—
Ot-H ₂ O					
10 ⁻¹	>150	>150	>150	TNTC	—
10 ⁻²	102	100	101	Countable	1,01 × 10 ⁴
10 ⁻³	8	10	9	TFTC	—
10 ⁻⁴	0	1	0,5	TFTC	—
10 ⁻⁵	0	0	0	TFTC	—
10 ⁻⁶	0	0	0	TFTC	—

Table 9: Determination of the total number of viable yeasts and molds (CFU/mL). TNTC – Too Numerous To Count, TFTC – Too Few To Count.

Dilution factor	Trial 1	Trial 2	Average number of colony-forming units (CFU)	Acceptability	CFU/mL
Ot					
10 ⁻¹	>180	>200	>190	TNTC	—
10 ⁻²	18	17	17,5	Countable	1,75 × 10 ³
10 ⁻³	2	1	1,5	TFTC	—
10 ⁻⁴	0	0	0	TFTC	—
10 ⁻⁵	0	0	0	TFTC	—
10 ⁻⁶	0	0	0	TFTC	—
Ot-H ₂ O					
10 ⁻¹	10	9	9,5	Countable	0,95 × 10 ²
10 ⁻²	1	1	1	TFTC	—
10 ⁻³	0	0	0	TFTC	—
10 ⁻⁴	0	0	0	TFTC	—
10 ⁻⁵	0	0	0	TFTC	—
10 ⁻⁶	0	0	0	TFTC	—

deposit still possesses a high proportion of montmorillonite and thus remains highly promising for use in composite material production.

3.9 Microbiological analysis

Fig. 8 and Table 8 present the results of the biological activity of Ot and Ot-H₂O samples against aerobic bacteria. Meanwhile, Fig. 9 and Table 9 comparatively illustrate the biological activity of Ot and Ot-H₂O samples against yeast and mold fungi. Aerobic bacteria are capable of living in organisms where oxygen exchange occurs, whereas yeasts and mold fungi represent widely distributed microorganisms found in nearly all living systems. Therefore, these microorganisms were selected for use in the microbiological analysis.

According to the Pharmacopoeia of the Republic of Kazakhstan, the microbiological purity analysis of Ot showed that the total number of aerobic microorganisms was 2.45×10^4 CFU/g, which exceeds the permissible limit ($\leq 1 \times 10^4$ CFU/g). The number of yeast and mold fungi reached 1.75×10^3 CFU/g, also surpassing the established standard ($\leq 1 \times 10^2$ CFU/g).

In Fig. 8a, small colonies with diameters of 0.1–0.2 cm are observed in the plates inoculated with serial dilutions of 10^{-1} , 10^{-2} , and 10^{-3} , distributed uniformly across the agar surface. In the plate with the 10^{-3} dilution (Fig. 8b), eight colonies with diameters of 0.2–0.5 cm developed. The colonies are circular, with smooth margins and a matte surface. Partial merging of colonies was noted in some areas. The Petri dish used had a bottom diameter of 90 mm.

In the Ot-H₂O sample, a significant reduction in microbial contamination was observed: the total number of aerobic microorganisms was 1.01×10^4 CFU/g, and that of yeast and mold fungi was 0.95×10^2 CFU/g. The reason for this is that during water activation, exchangeable ions are released from hydrolyzed water molecules and move freely.^[40]

These values fully comply with the pharmacopoeial requirements for non-sterile natural medicinal products. Based on the obtained results, it can be concluded that hydro activation of Ot bentonite enhances its biological activity. This, in turn, indicates its potential applicability as a base matrix for biopharmaceutical formulations in medicine.

In Fig. 9a, 18 colonies with diameters ranging from 2 to 18 mm were recorded in the Petri dish with the 10^{-2} dilution. In the dish with the 10^{-3} dilution, 2 colonies measuring 4–13 mm were observed. In Fig. 9b, corresponding to the activated sample, fungal growth was significantly reduced compared to the raw bentonite: in the dish with the 10^{-1} dilution, 2 colonies developed, while at the 10^{-2} dilution only 1 colony appeared. Their diameters were 5–11 mm and 9 mm, respectively. Based on morphological characteristics, the fungi were tentatively identified as belonging to the genera *Penicillium*, *Aspergillus*, and *Fusarium*.

The results showed that, compared with natural bentonite, the use of water-washed bentonite led to a reduction in the

number of fungal colonies. The high specific surface area and negative zeta potential of bentonite allow it to adsorb positively charged particles, including molecular complexes, toxins, heavy metals, and microbial cells.

Microbiological purity analysis of the raw clay established that the total number of aerobic microorganisms was 2.45×10^4 CFU/g, which exceeds the maximum permissible limit ($\leq 1 \times 10^4$ CFU/g) according to the Pharmacopoeial Monograph of the Republic of Kazakhstan. The number of yeasts and molds reached 1.75×10^3 CFU/g, also exceeding the established limit ($\leq 1 \times 10^2$ CFU/g).

In the purified clay, a significant reduction in microbial contamination was observed: the total number of aerobic microorganisms decreased to 1.01×10^4 CFU/g, while yeasts and molds decreased to 0.95×10^2 CFU/g. Based on morphological characteristics, they may belong to the genera *Penicillium*, *Aspergillus*, and *Fusarium*.

The obtained data confirm that the microbiological indicators of the activated bentonite fully comply with the pharmacopoeial requirements of the Republic of Kazakhstan for non-sterile natural-origin medicinal raw materials.

4. Conclusion

In this study, the physicochemical properties of bentonite from the newly identified Orta Tentek deposit in southeastern Kazakhstan were comprehensively characterized. The effect of hydro-activation with water on the elemental composition, phase and structural features, surface morphology, and textural parameters of Ot bentonite was systematically evaluated.

XRF analysis showed that Ot bentonite is mainly composed of SiO₂ (66.2%), Al₂O₃ (18.1%), Fe₂O₃ (8.0%), and Na₂O (2.09%), with minor amounts (~1%) of MgO, CaO, and TiO₂. The montmorillonite content was determined to be 93%, while the methylene blue adsorption capacity reached 93.2%. XRD analysis confirmed that the empirical formula corresponds to Na_{0.2}Ca_{0.1}Al₂Si₄O₁₀(OH)₂·nH₂O, consistent with sodium bentonite.

Hydro-activation significantly modified the structural and textural features of Ot bentonite. The average particle size of the plate-like granules decreased by ~1.5-fold, while the specific surface area and average pore size increased by 1.5-fold and 1.3-fold, respectively. XRD analysis revealed an expansion of the interlayer spacing (d-spacing) and a growth in crystallite size. Moreover, the sorption capacity improved to 96%, highlighting the enhanced performance of the hydro-activated Ot-H₂O sample. During the microbiological analysis, it was found that the aerobic bacterial activity of Ot-H₂O was 2.4 times higher than that of Ot, while the biological activity against yeasts and molds was 1.8 times greater.

These activations have important implications for practical applications. The increased d-spacing is particularly favorable for polymer intercalation in composite production, while the higher surface area and crystallite size improve the suitability of the material as a catalyst support. In addition, the enhanced sorption capacity makes Ot-H₂O a promising

candidate for use in environmental remediation (removal of inorganic and organic pollutants from water), in drilling fluids for the oil industry, and as a carrier material in pharmaceutical applications.

Acknowledgments

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19175733).

Availability of Data and Materials

All data generated or analysed during this study are included in this published article.

Conflict of Interest

There is no conflict to declare.

Supporting Information

Not applicable.

CRedit Statement

Madiar Beisebekov: Contributed by designing the study, Analyzing the data. **Sana Kabdrakhmanova:** Supervised and assisted in preparing, reviewing and editing the manuscript. **Nurgamit Kantay:** Assisted in preparing, reviewing and editing the manuscript. **Aryp Kadiran:** Data analysis. **Saule Nauryzova** and **Esbol Shaimardan:** Contributed by reviewing and editing the paper. **Kydyrmolla Akatan:** Reviewing and editing the manuscript. **Anastassiya Kukhareva** and **Lakhsbayeva Zhansaya:** Formal analysis. **Aigul Baibotayeva:** Contributed by reviewing. **Seilkhanov Tulegen:** Editing the paper.

References

- [1] A. Kalendova, J. Kupkova, M. Urbaskova, D. Merinska, Applications of clays in nanocomposites and ceramics, *Minerals*, 2024, **14**, 93, doi: 10.3390/min14010093.
- [2] P. Das, S. Manna, A. K. Behera, M. Shee, P. Basak, A. K. Sharma, Current synthesis and characterization techniques for clay-based polymer nano-composites and its biomedical applications: a review, *Environmental Research*, 2022, **212**, 113534, doi: 10.1016/j.envres.2022.113534.
- [3] A. S. Panasyugin, L. P. Dolgiy, I. L. Kulinich, A. A. Gerasikova, A. V. Mikishko, N. P. Masherova, A. R. Tsyganov, Trends in the use of bentonite clays, *Litiyo i Metallurgiya (FOUNDRY PRODUCTION AND METALLURGY)*, 2020, **4**, 78–89, doi: 10.21122/1683-6065-2020-4-78-89.
- [4] H. Desai, A. Kannan, G. S. K. Reddy, Sustainable and rapid pillared clay synthesis with applications in removal of anionic and cationic dyes, *Microporous and Mesoporous Materials*, 2023, **352**, 112488, doi: 10.1016/j.micromeso.2023.112488.
- [5] A. K. Jha, R. Thakur, S. Verma, T. M. B. U. B. India, S. Sikdard, Rare earth and trace metal characteristics of bentonite in the rajmahal hills, *ES Materials & Manufacturing*, 2023, **20**, 840, doi: 10.30919/esmm5f840.
- [6] P. Tabatabaie Shourijeh, A. Masoudi Rad, F. Heydari Bahman Bigloo, S. M. Binesh, Application of recycled concrete aggregates for stabilization of clay reinforced with recycled tire polymer fibers and glass fibers, *Construction and Building Materials*, 2022, **355**, 129172, doi: 10.1016/j.conbuildmat.2022.129172.
- [7] R. Rusmin, B. Sarkar, B. Biswas, J. Churchman, Y. Liu, R. Naidu, Structural, electrokinetic and surface properties of activated palygorskite for environmental application, *Applied Clay Science*, 2016, **134**, 95–102, doi: 10.1016/j.clay.2016.07.012.
- [8] S. Mnasri-Ghnmimi, N. Frini-Srasra, Removal of heavy metals from aqueous solutions by adsorption using single and mixed pillared clays, *Applied Clay Science*, 2019, **179**, 105151, doi: 10.1016/j.clay.2019.105151.
- [9] A. Kumar, P. Lingfa, Physicochemical characterization of sodium bentonite clay and its significance as a catalyst in plastic wastes valorization, *3rd International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech)*, August 29–31, 2019, Kolkata, India, 1–4, doi: 10.1109/iementech48150.2019.8981195.
- [10] Z. Huang, Y. Li, W. Chen, J. Shi, N. Zhang, X. Wang, Z. Li, L. Gao, Y. Zhang, Modified bentonite adsorption of organic pollutants of dye wastewater, *Materials Chemistry and Physics*, 2017, **202**, 266–276, doi: 10.1016/j.matchemphys.2017.09.028.
- [11] S. Jeenpadiphat, D. N. Tungasmita, Acid-activated pillar bentonite as a novel catalyst for the esterification of high FFA oil, *Powder Technology*, 2013, **237**, 634–640, doi: 10.1016/j.powtec.2013.02.001.
- [12] R. Antonelli, G. R. P. Malpass, M. G. C. da Silva, M. G. A. Vieira, Adsorption of ciprofloxacin onto thermally modified bentonite clay: Experimental design, characterization, and adsorbent regeneration, *Journal of Environmental Chemical Engineering*, 2020, **8**, 104553, doi: 10.1016/j.jece.2020.104553.
- [13] N. Khodabakhshloo, B. Biswas, F. Moore, J. Du, R. Naidu, Organically functionalized bentonite for the removal of perfluorooctane sulfonate, phenanthrene and copper mixtures from wastewater, *Applied Clay Science*, 2021, **200**, 105883, doi: 10.1016/j.clay.2020.105883.
- [14] A. Maged, S. Kharbish, I.S. Ismael, A. Bhatnagar, Characterization of activated bentonite clay mineral, *Environmental Science and Pollution Research*, 2020, **27**, 32980–32997, doi: 10.1007/s11356-020-09267-1.
- [15] A.A. Yessengulova, A.M. Yessengeldi, G.Zh. Kayralapova, R.S. Aminova, Zh.A. Abilov, M.M. Beisebekov, Synthesis of cryogels based on bentonite clay-polyacrylic acid and research their physical-chemical properties, *International Journal of Biology and Chemistry*, 2017, **10**, 92–96, doi: 10.26577/2218-7979-2017-10-1-92-96.
- [16] S. N. Zhumagaliyeva, R. S. Iminova, G. Z. Kairalapova, B. M. Kudaybergenova, Z. A. Abilov, Sorption of heavy metal ions by composite materials based on polycarboxylic acids and bentonite clay, *Eurasian Chemico-Technological Journal*, 2021, **23**, 19–27, doi: 10.18321/ectj1030.
- [17] A.I. Yagubov, L.A. Binnatova, N.M. Muradova, A.N. Nuriev, Wastewater purification using bentonite forms, *Russian Journal*

- of *Applied Chemistry*, 2010, **83**, 420–423, doi: 10.1134/S1070427210030092.
- [18] S. N. Zhumagaliyeva, R. S. Iminova, G. Z. Kairalapova, M. M. Beysebekov, M. K. Beysebekov, Z. A. Abilov, Composite polymer-clay hydrogels based on bentonite clay and acrylates: synthesis, characterization and swelling capacity, *Eurasian Chemico-Technological Journal*, 2017, **19**, 279–288, doi: 10.18321/ectj672.
- [19] S. Serikpayeva, N. Erzhanova, R. Iminova, S.N. Zhumagaliyeva, M. Beysebekov, Z.A. Abilov, Possibilities of composite materials use on the basis of polyvinilipirrolidon and bentonite clay as sorbents of heavy metals ions, *International Journal of Biology and Chemistry*, 2015, **8**, 77–80, doi: 10.26577/2218-7979-2015-8-2-77-80.
- [20] S. K. Kabdrakhmanova, A. Z. Kerimkulova, S. Z. Nauryzova, K. Aryp, E. Shaimardan, A. D. Kukhareva, N. Kantay, M. M. Beisebekov, S. Thomas, Bentonite-based composites in medicine: synthesis, characterization, and applications, *Journal of Composites Science*, 2025, **9**, 310, doi: 10.3390/jcs9060310.
- [21] S. Kabdrakhmanova, K. Aryp, E. Shaimardan, E. Kanat, B. Selenova, K. Nurgamit, A. Kerimkulova, A. Amitova, A. Maussumbayeva, Acid modification of clays from the Kalzhat, Orta Tentek deposits and study their physical-chemical properties, *Materials Today: Proceedings*, 2023, doi: 10.1016/j.matpr.2023.04.427.
- [22] L. G. Peng, J. H. Zhu, J. Han, X. X. Wang, M. Zhao, H. Q. Cheng, X. Zhang, Study on adsorption mechanism of acid-modified bentonite, *IOP Conference Series: Materials Science and Engineering*, 2017, **281**, 012009, doi: 10.1088/1757-899X/281/1/012009.
- [23] E. Vitale, D. Deneele, G. Russo, Influence of pore water chemistry on particle association and physical properties of lime-treated bentonite, *Minerals*, 2024, **14**, 795, doi: 10.3390/min14080795.
- [24] P. Warzecha, B. Hilger, S. Różycki, Bentonite clay suspension-coagulation process and identification of properties, *E3S Web of Conferences*, 2018, **49**, 00124, doi: 10.1051/e3sconf/20184900124.
- [25] K. Rybka, A. Kuligiewicz, S. Kaufhold, R. Dohrmann, A. Derkowski, Kinetics of rehydration in smectite and its application to water resorption in bentonites, *Applied Clay Science*, 2025, **271**, 107813, doi: 10.1016/j.clay.2025.107813.
- [26] A. Akhmetov, K. Nurbekov, S. Dyussembekova, Mineralogical and chemical composition of clays from southeastern Kazakhstan, *Minerals*, 2024, **14**, 321, doi: 10.3390/min14020321.
- [27] B. Kozhamkulov, et al., Structural and chemical properties of bentonites from the Alakol depression, Kazakhstan, *Applied Clay Science*, 2023, **232**, 106788, doi: 10.1016/j.clay.2023.106788.
- [28] D.P. Salo, F.D. Ovcharenko, N.N. Kruglickiy, Kyiv, Naukova Dumka, *Highly Dispersed Minerals in Pharmacy and Medicine*, 1969, 232.
- [29] J. D. G. Durán, M. M. Ramos-Tejada, F. J. Arroyo, F. González-Caballero, Rheological and electrokinetic properties of sodium montmorillonite suspensions, *Journal of Colloid and Interface Science*, 2000, **229**, 107–117, doi: 10.1006/jcis.2000.6956.
- [30] F. Bergaya, G. Lagaly, Developments in Clay Science, Amsterdam, Elsevier, *Clays and Clay Minerals*, 2006, **1**, 1246, ISBN - 978-0-08-044183-2.
- [31] U. Aroke, A. Abdulkarim, R. Ogubunka, Fourier-transform infrared characterization of kaolin, granite, bentonite and barite, *ATBU Journal of Environmental Technology*, 2013, **6**, 42–53.
- [32] V. K. Gupta, M. Sharma, R. K. Vyas, Hydrothermal modification and characterization of bentonite for reactive adsorption of methylene blue: an ESI-MS study, *Journal of Environmental Chemical Engineering*, 2015, **3**, 2172–2179, doi: 10.1016/j.jece.2015.07.022.
- [33] S. S. Gajbhiye, M. V. Salve, M. D. Gaikwad, A. R. Rasage, M. S. Khater, V. H. Ghadage and N. B. Chaure, Influence of Synthesis Conditions on the Physical Characteristics and Antibacterial Activities of Cerium Oxide Nanoparticles in Biomedical Applications, *Engineered Science*, 2024, **32**, 1254, doi: 10.30919/es1254.
- [34] J. L. Costafreda, D. A. Martín, Bentonites in southern Spain. characterization and applications, *Crystals*, 2021, **11**, 706, doi: 10.3390/cryst11060706.
- [35] T. Jamil, S. Yasin, N. Ramzan, H. M. Z. Aslam, A. Ikhlaiq, A. M. Zafar, A. Aly Hassan, Bentonite-clay/CNT-based nano adsorbent for textile wastewater treatment: optimization of process parameters, *Water*, 2023, **15**, 3197, doi: 10.3390/w15183197.
- [36] A. B. Mapossa, A. H. da Silva Jr, C. R. S. de Oliveira, W. Mhike, Thermal, morphological and mechanical properties of multifunctional composites based on biodegradable polymers/bentonite clay: a review, *Polymers*, 2023, **15**, 3443, doi: 10.3390/polym15163443.
- [37] W. D. Keller, R. C. Reynolds, A. Inoue, Morphology of clay minerals in the smectite-to-illite conversion series by scanning electron microscopy, *Clays and Clay Minerals*, 1986, **34**, 187–197, doi: 10.1346/ccmn.1986.0340209.
- [38] R. Pierotti, J. Rouquerol, Reporting physisorption data for gas/solid systems, *Pure and Applied Chemistry*, 1985, **57**, 603–619, doi: 10.1351/pac198254112201.
- [39] A. Zehhaf, A. Benyoucef, R. Berenguer, C. Quijada, S. Taleb, E. Morallon, Lead ion adsorption from aqueous solutions in modified Algerian montmorillonites, *Journal of Thermal Analysis and Calorimetry*, 2012, **110**, 1069–1077, doi: 10.1007/s10973-011-2021-8.
- [40] A. Kumar, P. Lingfa, Sodium bentonite and Kaolin clays: Comparative study on their FT-IR, XRF, and XRD, *Materials Today: Proceedings*, 2020, **22**, 737–742, doi: 10.1016/j.matpr.2019.10.037.
- [41] D. P. Kgabi, A. A. Ambushe, Characterization of South African bentonite and Kaolin clays, *Sustainability*, 2023, **15**, 12679, doi: 10.3390/su151712679.
- [42] A. Elgamouz, N. Tijani, I. Shehadi, K. Hasan, M. Al-Farooq Kawam, Characterization of the firing behaviour of an illite-kaolinite clay mineral and its potential use as membrane support,

- Heliyon*, 2019, **5**, e02281, doi: 10.1016/j.heliyon.2019.e02281.
- [43] W. K. Mekhamer, Stability changes of Saudi bentonite suspension due to mechanical grinding, *Journal of Saudi Chemical Society*, 2011, **15**, 361-366, doi: 10.1016/j.jscs.2011.03.014.
- [44] D. Sternik, A. Gładysz-Plaska, E. Grabias, A Thermal and sorptive study of HDTMA-bentonite, *Journal of Thermal Analysis and Calorimetry*, 2017, **129**, 1277-1289, doi: 10.1007/s10973-017-6384-3.
- [45] A.K. Mosai, L. Chimuka, E.M. Cukrowska, I.A. Kotzé, H. Tutu, The Recovery of Rare Earth Elements (REEs) from Aqueous Solutions Using Natural Zeolite and Bentonite, *Water, Air & Soil Pollution*, 2019, **230**, 1-17, doi: 10.1007/s11270-019-4236-4.
- [46] P. E. Belousov, B. V. Pokidko, S. V. Zakusin, V. V. Krupskaya, Quantitative methods for quantification of montmorillonite content in bentonite clays, *Georesursy*, 2020, **22**, 38-47, doi: 10.18599/grs.2020.3.38-47.
- [47] Y. Et-Tayea, A. Harrati, A. Rachid, H. Nasri, A. Attou, Y. Arkame, A. Manni, Y. Mamouch, A. El Bouari, F. El Khazanti, C. Sadik, Mineralogical and physico-chemical characterization of bentonite materials from the Oued Zemmour area (Oriental Rif, Nador-Morocco): Valorization in ceramic field, *Boletín de la Sociedad Española de Cerámica y Vidrio*, 2023, **62**, 268-283, doi: 10.1016/j.bsecv.2022.03.001.
- [48] P. C. Quero-Jiménez, L. A. Arias Felipe, J. O. Prieto García, M. E. Jorge Rodríguez, J. B. De la Torre López, O. N. Montenegro, R. Molina Ruíz, I. S. Tiscornia, Local Cuban bentonite clay: composition, structure and textural characterization, *Andean Geology*, 2021, **48**, 546, doi: 10.5027/andgeov48n3-3362.
- [49] B. Kussainova, G. Tazhkenova, I. Kazarinov, A. Nurlybayeva, A. Lamichova, L. Kusepova, T. Mashan, B. Tantybayeva, B. Saurbayeva, G. Seitbekova, D. Kulbayeva, R. Kudaibergenova, Comparative study of the physico-chemical properties of sorbents based on natural bentonites modified with iron (III) and aluminium (III) polyhydroxocations, *Coatings*, 2023, **13**, 1974, doi: 10.3390/coatings13111974.

exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

©The Author(s) 2025.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits the use, sharing, adaptation, distribution and reproduction in any medium or format, as long as appropriate credit to the original author(s) and the source is given by providing a link to the Creative Commons license and changes need to be indicated if there are any. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or